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REVIEWS

Design Informatics: Supporting Engineering Design Processes with Information Technology

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Abstract | Engineering design is an information processing activity, in which designers access and create information at every stage of the design process, creating information models of the designed artefact and to assist in the evaluation of its performance. The importance of information in design has meant that design informatics—the use of computers as a means of generating, communicating and sharing data, information and knowledge in design—has been a central theme in the design research and practice for many years. This paper reviews the progress of research in design informatics, and makes suggestions for future research directions using as a basis for structuring the discussions Gero's function-behaviour-structure and Weber's characteristic-properties models of design activities. The review encompasses technologies of computer-aided design, computer-aided engineering, computer-supported collaborative work, design-for-X and knowledge and information management among others, with an emphasis on applications in mechanical engineering and related disciplines.

1 Introduction

The exchange of information has been described at the lifeblood of product development.[1] When engineers propose the design of a new artefact, they refer to information about the requirements of the customer and about the constraints within which they will work (including for example the properties of available materials and the capabilities of manufacturing processes). They search for and study information about previous designs, the obligations of standards and so on. In the course of the design process, physical concepts are proposed and developed, and are recorded in an information model of the new artefact. Further information models are used to evaluate the fitness for purpose of the proposals from viewpoints such as performance, structural integrity, manufacturability, emissions and cost, and results of the evaluation are used to inform the development of the design. The creation, manipulation and access of information are of central importance at every stage of the design process, and thus the use of information technologies within the design process has been a dominant theme of design research and practice for many years.

The term **informatics** has, in recent decades, come into widespread use to describe the information sciences concerned with data creation, processing and retrieval. Raphael and Smith[2] describe **engineering informatics** as the use of computers as a means of generating, communicating and sharing data, information and knowledge in engineering, while Subrahmanian and Rachuri[3] stress its role in facilitating the practice of engineering to achieve social, economic and environmental goals. It is suggested that **design informatics** comprise a sub-set of engineering informatics. Horvath[4] sees it as aiming 'at studying all design-specific aspects of handling data and knowledge related to humans, products and tools', while Shah *et al.* define it as the science of the use of information and knowledge to support knowledge-intensive design.[5] These definitions provide the broad boundaries for this paper.

Of course design informatics is not the only term used to describe the use of computers in

Engineering informatics: The use of computers as a means of generating, communicating and sharing data, information and knowledge in engineering.

Design informatics: Computer-based handling of data and knowledge in the design process.

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Computer-aided design (CAD): The use of computers in the modelling and representation of the structure and physical attributes of engineered artefacts.

Computer-aided engineering (CAE): The use of computing technologies to evaluate the performance of engineered artefacts through simulation and analysis.

Computer-aided manufacturing (CAM): The use of computers to support the generation and application of manufacturing data.

Product lifecycle management (PLM): The organisation and management of product data through the life or the artefact, especially with computer assistance.

Information management (IM): The collection and management of information as an organisational resource.

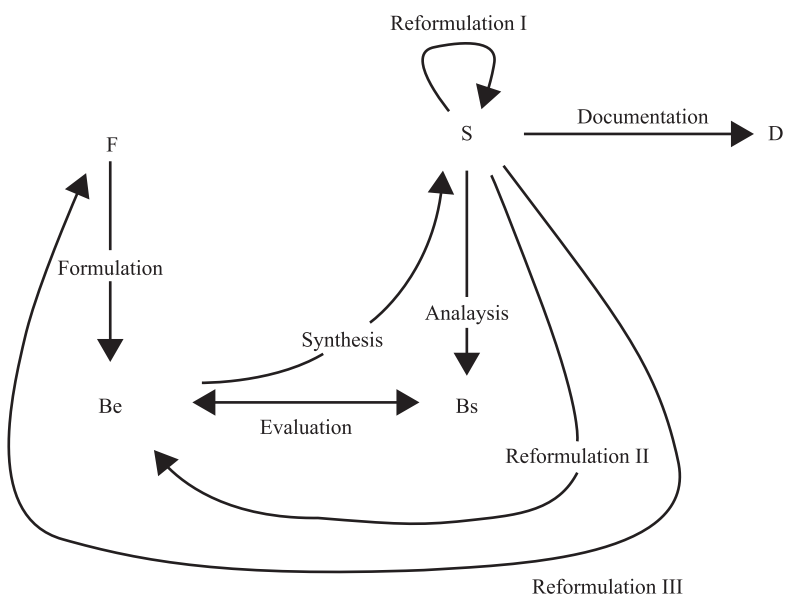
Knowledge management (KM): Activities for the effective sharing and management of knowledge within an organisation.

Computer-supported collaborative work (CSCW): The use of computing technology to support communication, sharing and collaboration in working activities.

support of the design process. **Computer-aided design (CAD)** has come to be used ubiquitously for the modelling of the structure and physical attributes of engineered artefacts, while the more general term **computer-aided engineering (CAE)** encompasses CAD and also the computing technologies used, for example through simulation and analysis, to evaluate the performance of the artefacts. **Computer-aided manufacturing (CAM)**, as the name implies, describes the use of computers to support the generation and application of manufacturing data, while CADCAM is a general term for the combined application of CAD and CAM. The wider management of data in engineering and product development is termed engineering data management (EDM) or product data management (PDM), although more recently **product lifecycle management (PLM)** has become the most widely used term, reflecting the importance of engineering data through the life of the artefact. The trend in engineering in recent years has been for all of these applications to become more closely interlinked, and a number of large software vendors sell suites of software that deliver all of these applications.

There are also computing technologies that are important in design that are also widely used outside of design. **Information management (IM)** and **knowledge management (KM)** are used by communities of all descriptions to manage their information and knowledge, and the technologies of **computer-supported collaborative work (CSCW)** are used to support the interaction among members of teams. The application of all of these techniques, and others, is the focus of this article. Some boundaries have to be placed on such a broad topic—the article will concentrate on design in applications such as mechanical, automotive and aerospace industries, and will only make passing mention of application in built environments, or electrical and electronic design.

In order to understand better the way in which computing applications have developed and how they relate to each other, it is helpful to consider them with respect to a high-level view of the nature of design and of the design process. Two such views are used here are Gero's Function-Behaviour-Structure (FBS) model of design,[6] and Weber's description of design as focusing on the characteristics and properties of artefacts.[7] In FBS, designs are created in order to achieve particular **functions**, i.e. what is required of the design. These are expressed in terms of **desired behaviour** of the artefact. Designers propose **structures** (i.e. organisations and forms of the artefact) in order to achieve this desired behaviour. A variety of approaches (analytical, computational and experimental) are then used to explore the **actual**



F = required functions; Be = desired behaviour;
S = structure; Bs = achieved behaviour; D = documentation
Reformulation I changes structure to try to achieve desired behaviour.
If this does not succeed then Reformulation II modifies desired behaviour.
If that does not succeed then Reformulation III modifies required function.

Figure 1: The function-behaviour-structure (FBS) model of design.[6]

behaviour of the structure. The functions, desired behaviour or structure may then be modified iteratively until a satisfactory solution is obtained, as shown in Figure 1 (adapted from [6]). When the process is complete a record is made of the result, especially of the designed structure, in the form of instructions for manufacture. Note that the term 'behaviour' is used here to describe the attributes used in a very general sense to judge the performance of the emerging design with respect to the design requirements.

Weber extends the argument made by Gero by observing that the structure of the artefact corresponds to its **characteristics**—its form, arrangement, surface condition and so on, and the behaviour is expressed in terms of the **properties** of the artefact—its strength, its thermal characteristics, its performance and so on, as shown in Figure 2. It follows that the activities of the design process include searching for the characteristics of the artefact necessary to achieve particular functions and behaviours (i.e. certain properties), and also estimating, predicting or otherwise exploring the properties of a proposed artefact design with particular characteristics when placed in a given environment. The whole process needs to be documented, and the designer will very often wish to refer to previous design episodes to explore the structures used and the decisions made. All the work is done in the context of particular enterprises and national and international arrangements, and is therefore subject to standards. All of these considerations point to the design activities that need to be supported computationally—modelling characteristics; modelling properties; choosing characteristics to give desired properties; choosing structure to give functions; supporting social processes; capture of rationale and past choices; indexing and searching historic data and providing an engineering framework for all activities. This characterisation of activities forms the basis for the structure of this paper.

2 Modelling Artefact Characteristics

It has been argued that engineering design, broadly as we know it today, emerged from craft traditions in the renaissance with the use of drawings to record the form and structure of the intended artefact, a development which allowed the designer to develop ideas more incrementally, to deal with complexity and to share with others.[8] Once drawings were used, for example to describe the intended structure and form of a ship, analytical

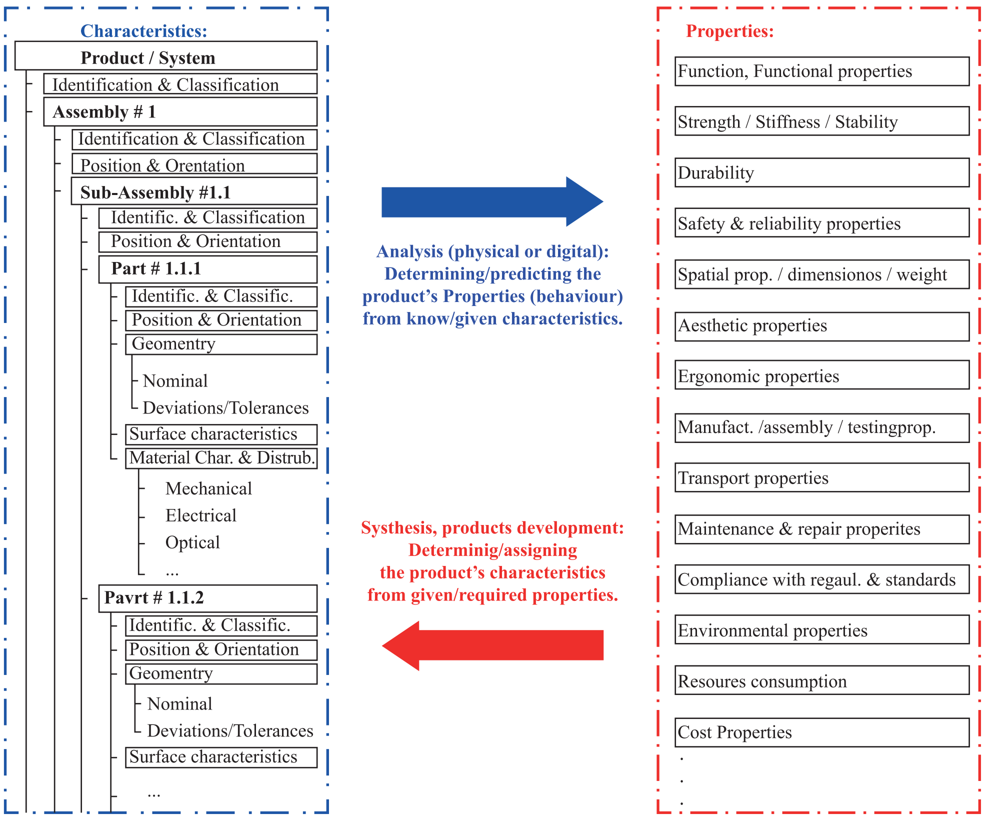


Figure 2: Artefact characteristics and properties.[7]

techniques could be used to calculate such properties as the centre of mass or the centre of buoyancy.[9] This use of 'measured plans' developed into the current practice of using drawings to represent the arrangement and form of the artefact (for example drawings of the parts of an engine), and diagrams to record structure in terms of the elements involved and their relationship to one another (for example electrical circuit diagrams). The descriptive geometry approach used in orthographic projection drawing was formalised by Monge in France in the early 19th century.[10]

In the middle of the 20th century, a number of technical developments allowed the emergence of computational techniques for the representation of geometry. The development of **numerical control (NC)** of machine tools allowed greater precision and repeatability in the manufacture of parts, but called for new approaches to the description of geometry.[11] The complex doubly-curved surfaces used in aircraft, ships and automobiles reinforced that need, while the development of graphical computer displays allowed approaches to be explored in which geometric representations could be created and manipulated interactively. The 1950s, and in particular the 1960s, led to a flourishing of developments: the Automatically Programmed Tools (APT) language for the representation of machined parts,[12] interactive creation and manipulation of geometry in Ivan Sutherland's Sketchpad,[13] Bezier curves and surfaces for shape representation—especially for example for automobile body design[14] and early commercial use of systems for the application of geometric modelling.[15]

The end of the 1960s also saw the development of **solid modelling**, which has become the dominant paradigm for geometric modelling in CAD. Research was concentrated on a number of competing approaches from which two emerged most strongly: **boundary representation (B-rep)**, first developed at the University of Cambridge in the late 1960s in the BUILD system,[16] and the set-theoretic approach of **constructive solid geometry (CSG)** used in the University of Rochester's Production Automation Description Language (PADL), in which set-theoretic operations were used to combine geometric primitives.[17] Modern systems are predominantly based on the B-rep paradigm, but incorporate the set-theoretic operations of CSG. Modern solid modelling systems are able to model geometries with free-form surfaces modelled using the **non-uniform rational B-spline (NURBS)** form, chosen because analytic curves, Bezier curves and other spline curves can all be modelled using NURBS geometry, allowing a modelling system to use a single internal representation.[18]

B-rep modelling and NURBS curves and surfaces provide a powerful means of modelling shape. For the modelling of structure in electrical circuits, the **netlist** models the components in the circuit and the conductors connecting them, and has become a key part of electronic CAD (eCAD).[19] In mechanical engineering, the hierarchical decomposition of an assembly into sub-assemblies and parts is modelled as a **bill of materials (BOM)**, which is the fundamental data structure in PDM, EDM and PLM systems.[20]

The emergence of solid modelling was driven by the notion that description of the 3D geometry of parts is the foundation on which other engineering applications would be built—such as the generation of tool paths for NC tools or the generation of models for engineering analysis—but much engineering work still required extensive human interaction to recognise the shapes that corresponded to the particular engineering functions. An important early example of this was the manufacturing **process planning**—identification of the sequence of operations required to make a part. This led to attempts to recognise geometric and other patterns with engineering significance, which were termed as **features**; the process plan would be built from the feature model. While a lot of progress was made, generalised feature-recognition is still resource-intensive and partly unsolved, especially when features intersect.[21] An alternative to feature-recognition is to design explicitly in terms of features, and in the 1980s and 1990s there was a good deal of research on **feature-based design** or design-by-features.[22] Again, this was partly successful—many modern CAD systems allow users to construct geometry as a collection of editable features—but the viewpoint dependence of features (the feature-set required by a manufacturing engineer may be incommensurate with that required by a stress analyst) has meant that they have not proved to be as powerful as once expected. Researchers are still exploring alternatives to feature-recognition and design-by-features such as annotation,[23] and the issue of features has developed into a more general one of accessing and representing product semantics.

Another issue that is still very active is that of the automatic generation of artefact representations and the identification of representations that are readily reused and modified. One of the advantages of CAD that was identified very early was the possibility to reuse

Netlist: A description of the components in a circuit and how they are connected.

Bill of materials (BOM): A hierarchically decomposed list of the assemblies, sub-assemblies and components required to build an artefact.

Numerical control (NC): The use of servo-machinery to enable the control of machine tools using pre-programmed commands.

Process planning: Identifying the sequence of manufacturing operations required to make a part or assembly.

A feature: A geometric or other pattern, often on a part, with engineering significance (e.g. a hole or a pocket).

Feature-based design: Construction of models of engineered artefacts from features (typically in CAD).

Solid modelling: The use of computers to model the 3-dimensional geometry of an artefact allowing identification of whether a point is inside, outside or on the surface of the artefact.

Boundary representation (B-rep): Solid modelling by considering the artefact as a body or bodies, bounded by faces, in turn bounded by edges, joining at vertices.

Constructive solid geometry (CSG): Solid modelling through the set-theoretic combination of geometric primitives.

Non-uniform rational B-spline (NURBS): A mathematical model used for representation of curves and surfaces using polynomial spline functions.

geometry (for example in patterns representing fasteners, machine elements and the like), and commercial CAD systems incorporated programming languages for the programmatic execution of system functions. These allowed programs to be written for the automatic construction of custom-variable parts such as gears, and other system customisation.[24] A development of this approach is **knowledge-based engineering (KBE)**, in which a geometric modelling capability is combined with the programmatic and inference capabilities of an expert or knowledge-based system, offering significant possibilities for the capture and re-use of product knowledge. While significant progress has been made in KBE, the programming effort required, the necessity for methodological support and need for better transparency and traceability of knowledge has been a limitation.[25] KBE has also been overtaken to a certain extent by parametric and associative CAD systems becoming more or less ubiquitous. These systems support, at least in principle, easy editing and reuse of geometry without the need for programming, for example by the maintenance of a re-executable history of the steps used in constructing a model, although in practice users often find the methodological rigour needed to create a good model challenging.[26]

Today, parametric-associative CAD systems using B-rep modelling and NURBS and with a feature-modelling capability, and PLM systems based on BOM, are the *de facto* standard approaches in industry. Product semantics and the link to other viewpoint models are the current research issues, as are computational techniques for the exploration of the design space (as will be seen in a later section). There has also been considerable work on taking product representations into **virtual** and **augmented reality** (VR and AR), with widespread experimental work and some industrial applications,[27,28] although the approaches are still far from ubiquitous.

3 Modelling Artefact Properties

The prediction of artefact 'behaviour' in its most general sense is achieved in a variety of ways—using classical analytical techniques, through empirical relationships, through model or prototype manufacture and test, and through numerous computer-based analytical methods. These methods predict the behaviour of the artefact from multiple engineering viewpoints (MEV)—structural, thermodynamic, kinematic, cost and so on,[29,30] generally by evaluating the properties of the artefact when placed in a particular environment or subject to particular loading conditions. This evaluation was originally carried out independently of the modelling of artefact characteristics, necessitating lengthy manual model interpretation and building, but more recently, significant steps have been made to integrate modelling approaches, either by passing data between tools (e.g. from a CAD tool to a structural analysis tool) or by embedding analytical tools into CAD systems.

The dominant engineering analysis approach, for many years, has been the **finite element method (FEM)**, a numerical method for the solution of engineering problems in areas such as structural analysis, heat transfer, vibration and electromagnetic potential. Other related approaches are the **boundary-element method** (BEM) and **computational fluid dynamics (CFD)**. The methods are well-described elsewhere.[2] For the purposes of this article it is noted that the fundamental geometric representations used in FEM, BEM and CFD differ from those in CAD: these essentially use cell decomposition—they divide shapes (or, in the case of the BEM, the boundary of a shape) into a number of discrete co-adjoining elements, whereas in CAD, the boundary representation or CSG approaches are used. The consequence is that a mapping from the CAD representation is needed in any preparation of a model for analysis. This 'mesh generation' issue (so-called 'pre-processing') has been a dominant one in CAE for many years, and has involved techniques for the mapping of nodes into a space, and for the sub-division of that space.[31,32] Once the analysis has been carried out, mapping of the results from the nodes and elements back to the original geometry is also an issue, although often this step is omitted. The ultimate aim is to be able to generate a finite element model directly from the CAD geometry (with loads and boundary conditions defined by annotation of the CAD model). This has largely been achieved, but there remains the issue that very often the CAD model contains details (e.g. chamfers, fillets, small holes etc.) that are not needed for analyses. Numerous techniques have been developed for this purpose[33] but it is still a current research issue, and related to the feature-recognition/semantics question described in the previous section.[34]

The application of FEM in design has been developed very extensively in recent years, including the coupling of analyses from multiple physical perspectives,[35] the combination of the results of structural analysis with damage accumulation in fatigue analysis[36] and the design of composite materials which presents challenges in CAD and FEM.[37] These developments have been

Knowledge-based engineering (KBE): Combination of ageometric modelling (CAD) capability with the programmatic and inference capabilities of an expert or knowledge-based system.

Finite element method (FEM): Numerical methods for the solution of engineering problems based on the subdivision of a body into discrete elements.

Boundary-element method (BEM): Numerical methods for the solution of engineering problems based on the subdivision of the boundary of a body into discrete elements.

Computational fluid dynamics (CFD): Numerical methods for the solution of engineering problems involving fluid flow.

Virtual-reality: The computer-generated simulation of 3-dimensional environments or objects.

Augmented reality: Superimposing of a computer-generated simulation of 3-dimensional environment or object on a user's view of the real world.

Optimisation: Identification of the design characteristics that give the best value for some objective function.

Constraint modelling: Exploration of the design space defined by a set of constraints on the design's characteristics or properties.

Design for manufacture and assembly (DFMA): Methods for assessing and improving the ease of manufacture and assembly of artefacts.

Design-for-X (DFX): Methods for assessing and improving the properties of a designed artefact, where properties can include reliability, durability, maintainability, sustainability and many other factors.

Computational design synthesis (CDS): The use of computers for the algorithmic creation of new designs.

Life cycle assessment (LCA): Tools and methods for the evaluation of the environmental impact of a product, process or service.

supported by the creation of extensive databases of materials properties,[38] and the development of sophisticated visualisation and data presentation techniques.

The FEM and related techniques can be used for the evaluation of properties that can be modelled by suitable systems of equations, but there are many engineering properties, such as manufacturability, maintainability and so on (often called the 'ilities'[39]), which are evaluated by more empirical approaches. In these cases, there has been widespread exploration of techniques which use a rating process that assigns scores to certain features or characteristics of the artefact on the basis of collected empirical data. The best known among these approaches are those for **design for manufacture and assembly (DFMA)**,[40] but many other **design-for-X (DFX)** techniques (where X is some property) have been developed.[41] The input to these is very often manual, but a number of approaches have been developed to try to integrate them with CAD tools, especially through the use of feature-recognition or feature-based design.[42]

Research into DFX continues strongly,[43] especially in matters concerning the environmental impact of engineered artefacts. Topics include design for disassembly,[44] design for recycling,[45] design for remanufacturing[46] and the techniques of **life cycle assessment (LCA)**. LCA is a systematic approach to the computation of the environmental impacts of an artefact by considering its characteristics, all of the processes used in its manufacture and support and the impacts of its use through life and disposal. To achieve a satisfactory evaluation requires extensive information from all phases of the product life cycle and therefore LCA is very challenging to use in design,[47,48] especially in the early stages, although a number of lightweight approaches have been developed to assist in making design decisions.[49] The integration of LCA into CAD and PLM is currently an active research topic.[50]

4 Choosing Characteristics to Achieve Desired Properties

If the computational capabilities to model an artefact's characteristics are combined with those for prediction of its properties, then the necessary characteristics to achieve some desired properties may be methodically explored. This is most easily be done for the case of searching the design space of a particular design principle, and has been widely implemented in design search and optimisation methods. These typically operate using parametric representations of the artefact, and the design space is explored by systematically varying the parameters. Computational tools have been developed, which allow the repeated generation of parametric CAD and FE models allowing **optimisation techniques** to be applied (typically by modelling data flows using a network model and using scripts to execute the parametric models).[51] They also permit stochastic exploration of the design space, including coupled and multi-physics analyses, the generation of response surface models relating properties to the design parameters and the like. Design space exploration in mechanism design has been achieved through **constraint modelling.**[52] The techniques have found wide application in many areas of engineering.[53,54]

In addition to the exploration of parametric design spaces, there has also been a good deal of work on topological exploration—the process of determining the optimum layout of material and connectivity in a design domain.[55] Significant progress has been made in structural design, but exploration of topologies involving arbitrary combinations of features remains challenging, as does the more general computational problem of proposing a structure (in the broader sense of a design arrangement) to provide a particular set of functions. This comes within the domains of **computational design synthesis (CDS)** or automated design synthesis (ADS), which encompass such issues as how to represent functions and how to provide a grammar and rules for the legitimate combination of design elements.[56,57] Recent work has reported automated design synthesis strategies for topological and parametric design exploration using graph grammars.[58]

5 Capturing the Process and Rationale

While drawings, diagrams and CAD models capture the desired characteristics of the artefact, FE and other models capture what the likely properties of the artefact are in a given environment. But neither record why the artefact design is the way it is, or what has been the basis for design decisions. This has traditionally been the role of documents such as specifications, design reports, meeting minutes and the like, though such documents are not computationally interpretable (or at least not without sophisticated natural language processing ability). Computational systems have, thus, been used to attempt to capture, in a more formal or computationally tractable way, the process by which the design has been produced and the rationale behind design decisions.

Design activities involve both synchronous working—when participants in the design process interact in real time such as in meetings—and asynchronous working, when they work independently with interaction, for example by mail.[59] Badke-Schaub and Frankenberger distinguished between the **critical situations** in design, where choice is made or the process takes a new direction on a conceptual or embodiment design level, and **routine design**, where the participants undertake work to develop the current concepts or framework.[60] It is suggested here that different computational approaches are needed to document design work during the collaborative, synchronous, critical situations than during the individual working and more asynchronous modes of routine design; this can be seen in the recent work that has been carried out.

Central to the work to capture critical situations in design have been two strands of work—**design rationale capture** and **meeting capture**. Design rationale capture has been studied for many years,[61] but in recent years a strong line of research has developed using the graphical representation techniques of the long established issue-based information systems (IBIS),[62,63] and the use of such approaches has been mandated in major engineering companies.[64] These approaches offer a rapid means of capturing the discourse on design rationale in a design episode. Meeting capture research, on the other hand, aims to use video and audio techniques, combined with graphical browsing, to capture a rich record of a design meeting.[65] Current work includes research into the incorporation of automatic transcription of dialogue in such meetings.[66]

It is suggested that the capture of routine design activities is much more transactional: for example a designer collects information on part geometry and constraints to carry out geometric or other explorations of design feasibility, or a design analyst collects information on geometry, materials and loads for a structural evaluation. In this case the challenge is to document the information used, the exploration/evaluation (the transaction) and the result. Computational approaches have been explored based on approaches used in design automation and on modelling the activities as state-transitions[67] or tasks.[68] Recording the designer's interactions with computer tools (the 'key-stroke logs') may allow records to be constructed automatically using a transaction model.[69] This remains a task for current research, but the automated documentation of design processes is also a challenge because of the multi-layered nature of the design process, as shown in Table 1. This figure shows that in a typical design process, individual participants interact with design tools on a second-by-second basis. Small groups generate data sets and make decisions in a timescale of hours or days. For large teams the timeframe may be months or even years, and as information is moved between layers, decisions have to be made about what is important and what to include in documentation.

Although automated documentation is challenging, there are interesting developments exploring what can be learned about the progress of engineering projects by examining the data produced by the project team in the course of their work—for example to monitor the rate of progress in CAD model construction or to trace the topics

Critical situations: Design situations, typically collaborative, where a choice is made, or the process takes a new direction on a conceptual or embodiment design level.

Routine design: When participants undertake routine work to develop the current concepts or framework of a design.

Design rationale capture: The creation of a record of the explicit reasons behind decisions made when designing an artefact.

Meeting capture: The creation of a record of the discussions and decisions made in a meeting.

Table 1: Information layers in design projects.

Design process elements	Modelled by	Participants	Deliverables	Timescales
Stages	Stage Gate models	Inter-company Teams	Large-scale information packages	Months–Years
Work Packages e.g. Durability Evaluation	Gantt charts, Design Structure Matrix	Company/ inter-company teams	Information packages	Months–Years
Tasks e.g. structural analysis	Gantt charts, Design Structure Matrix	Work groups	Information packages	Weeks–Months
Activities e.g. FE Analysis	IDEF0, UML Activity diagrams	Small teams	Information objects e.g. CAD models	Hours–Weeks
Operations e.g. modelling a constraint	State transitions, Petri nets	Individuals	Features and elements of information objects	Minutes–Hours
Actions/Events e.g. selecting CAD model face	Event logs	Individuals	Manipulation at GUI and entity level	Seconds–Minutes

Big data: Large data sets that may be explored for the identification of patterns.

Cloud computing: A type of computing in which data are stored on servers and accessed through the Internet.

Knowledge-organisation structures (KOS): Classification structures, taxonomies, and ontologies used for the organisation of computational information and knowledge.

in email exchanges.[70] This work points the way to the use of engineering data in '**big data**' applications and for project health monitoring, applications that would be strongly supported by the use of **cloud computing** for data storage.[71]

6 Supporting the Design Actors

Rationale capture and meeting capture are part of a wider system of support for the participants in the design process through computer-supported cooperative working (CSCW) and through knowledge and information management. CSCW is "computer-assisted coordinated activity carried out by groups of collaborating individuals"[72] and comprises many techniques (most of which are widely adopted in many contexts) used to support synchronous and asynchronous working. Table 2, adapted from [72], shows some of those aspects of CSCW that have been most widely applied in design, together with reference to certain of the key design research works on the topic. A useful critique of computer support for collaborative design processes is provided by Perry and Sanderson.[73]

Research in CSCW leads more generally to research into what should be the general framework to provide support for collaborative design activities, including what is the nature of the discourses that need to be supported (and how),[80] and what aspects of complex product development need to be captured and coordinated.[81] These are still active research topics.

Information search and retrieval (IS&R): The use of computers to search for and retrieve information itself stored on computer systems.

Computer-based storage and developments in communication and networking technologies permit, in principle, much easier means of searching and retrieving a wide range of relevant digital textual information, both within and external to organisations. The most common **information search and retrieval (IS&R)** approach has been the use of free text search engines, and the success of such search tools for Internet content means that free text search is now ubiquitous. It does not always work so well in a non-hyperlinked environment, however (for example the internal documents of a company), in which case other IS&R strategies may be worthwhile. A number of approaches have been used in design, especially using predefined types of **knowledge-organisation structures (KOS)**. Essentially, by spending time up-front: (i) organising information (ii) associating documents with pre-identified standard subject categories and/or (iii) identifying relationships between these categories, relevant information can be more easily located and retrieved at search time. Categories of KOS used in design include classification schemes, which emphasize the creation and organization of subject sets, e.g., subject headings, classification schemes, taxonomies and categorization schemes—and relationship lists—which emphasize not only the creation and organization of subject sets, but also the connections between the terms and concepts within them e.g., thesauri, semantic networks and ontologies. The use of faceted classification and ontologies have been particularly strong research themes in design and interest is still continuing.[82–85] More generally, understanding the designer's use of information systems and how they may assist has for many years been a strong research topic in engineering design, and future systems will be built on that understanding.[86]

7 Standards for Curation and Exchange

A consequence of the widespread use of digital tools in engineering design has been a very strong emphasis over many years on the development of appropriate standards to ensure that data are compatible and interoperable, and that data can be sustained over long timescales.[87] The term 'curation' has been used to describe the active and ongoing management of digital data, emphasising the need for managed caring of data.[88]

The use of standards broadly maps onto the categories of design activity that have been explored in this paper. Because of the importance of being able to exchange data about the designed artefact between participants in the design process and throughout the life of the artefact, there has been continuing emphasis on standards for CAD models from the Initial Graphics Exchange Specification (IGES) of the late 1970s to the very extensive ISO10303 standard for product data representation and exchange (informally known

Table 2: A classification of CSCW in design.

	One meeting place (Co-Located)	Multiple meeting places (Distributed)
Synchronous communication (same time)	**Face-to-face interactions** Electronic meeting rooms Group decision support systems[74]	**Remote interactions** Video conferencing[75] Shared desktop and collaborative editing[76]
Asynchronous communication (different times)	**Ongoing tasks** Team rooms and collaborative environments[77]	**Communication and coordination** Email Workflow management[78] Message and bulletin boards[79]

as the STandard for Exchange of Product data—**STEP**).[89,90] The latter ensures that CAD models constructed using the current B-rep paradigm may be reliably stored and interchanged. More recent work has explored how models of construction history used in parametric models, and the notions of design intent, may be captured.[91,92]

Standards have also been extensively developed for capture of the models used in the evaluation of artefact properties, but although the models used in finite element and other analyses may be captured using the STEP standard, the range of properties to be modelled is so potentially large that many 'ilities' are not completely covered by standards. Subjects of current research interest include the capture of the processes of model building and execution in simulation data management (SDM), and systematic capture of the relationships between the models used in particular design episodes.[93,94]

Beyond CAD and CAE, standards are also important in all of documentations used throughout design and for the data that are collected through the life of the artefact. The U.S. military was originally a strong driving force in this regard through its **computer-aided acquisition and logistics support** initiative (CALS—later continuous acquisition and logistics support), which prescribed the use of IGES and STEP data for CAD but also standards for images, for text documents and so on.[95] More recently, product life-cycle support (PLCS) has been developed as an application protocol of STEP for through-life support, and the ISO open archival information system (OAIS) approach has been applied to engineering archives.[96] For the future, comprehensive standards are likely to be one of the pillars on which 'big data' applications and '**open innovation systems**' in engineering design are built,[97] and the increasing importance of sustainability issues could raise the emphasis on through-life data management and the need to incorporate life cycle analysis into engineering standards.[98,99]

8 Future Challenges

Enormous progress has been made in design informatics, and almost every aspect of the engineering design process is supported by computational tools, but there is a great deal still to be done. Importantly, the support for the more creative parts of the design process is limited—most tools apply in the later embodiment and detail design phases, and even in these areas the development of CAD tools has somewhat stalled—the main parametric-associative boundary representation paradigm was established in the late 1980s and is still in use today. The models produced in design often have practically no semantic content, and CAD tools have a very limited capability to mix electrical, electronic, software and mechanical models.

The exploitation of the very large quantities of data generated in engineering design activities has also hardly begun. In this regard it is suggested that two key issues have to be addressed. Firstly, most design information and knowledge is proprietary and is not shared openly by those organisations that own it. New ways are needed to capture, document and disseminate design knowledge: for firms to share information not directly related to their artefacts (e.g. cost data, manufacturing capability and methods, embodiment and detail design principles), for design issues in different industry contexts to be described in a common language such that designer mobility and diffusion of ideas is encouraged. Secondly, new ways are needed to learn from the very extensive data that we have about the performance of analytical tools, to allow those tools to be validated. This will require access not only to the data from modelling events, but rich data on the relationships between models and about the processes by which they were constructed. Design informatics research over the past decade provides a solid foundation for such work.

9 Conclusions

The importance of information to the engineering design process has meant that the application of computers in engineering design—i.e. design informatics—has been a central theme of research for in the order of half a century. Enormous progress has been made, such that the use of computers is embedded in all aspects of design practice, especially in the modelling of the designed artefact and in the support of designers and design teams in many aspects of their communication, collaboration and information and knowledge management. But while computer applications are ubiquitous in design, a number of areas have proved very challenging, and a significant number of unsolved issues remain. In particular, design informatics has had little application in the creative, fuzzy early phases of design, the main representations used in CAD and CAE are geometric and lack semantic content, there is very poor integration of tools for mechanical, electrical and electronic applications and the possibilities of exploiting the vast quantities of data created in design have hardly been explored. The resolution of these

STEP standard: International Standard ISO10303 for the definition and storage of computer-based product data.

Continuous/computer-aided acquisition and logistics support (CALS): A United States Department of Defense initiative for the computer-based definition of data used in military procurement and equipment support.

Open innovation systems: Collaborative frameworks in which a variety of stakeholders contribute to the development of innovative products and services.

issues and other issues offers an exciting research agenda for the next half century.

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